**Research Report**

Research Project T9234-11

Stormwater Contaminant Removal by Chemicals

# ENHANCING CONTAMINANT REMOVAL IN STORM-WATER DETENTION BASINS BY COAGULATION

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Department of Transportation
and in Cooperation with
**U.S. Department of Transportation**
Federal Highway Administration

STANDARD RESEARCH REPORT TITLE PAGE

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**TABLE OF CONTENTS**

**LIST OF TABLES and FIGURES**

## EXECUTIVE SUMMARY

Urban development and expansion has increased stormwater loads on receiving waters, forcing planning agencies to address both point and non–point source discharges of stormwater. Control of highway runoff pollutant loading has become a high priority for many planning agencies. Washington Department of Transportation (WSDOT) has implemented programs aimed at limiting pollutant loads to receiving waters from highway runoff. Management practices which have traditionally targeted flood control are now incorporating measures to limit contaminant loads. Detention basins for example, designed initially for flood prevention, have been found to remove significant quantities of sediment. Other contaminants (e.g., metals) partitioned on these sediment particles are also removed. The smaller sediment size fraction that escapes the detention basin contain the majority of partitioned contaminants, however (Cole and Yonge, 1993).

Increased metal removal in detention basins could be realized through the enhancement of smaller particle removal. This can be achieved through the use of chemical coagulants. The effectiveness of chemical coagulation in stormwater detention basins has not been investigated, however. Consequently, batch and continuous flow, scale model studies were used to asses the impact of coagulant addition on contaminant removal. Four coagulants were evaluated with respect to contaminant removal in both bench and scale model detention basin experiments. Adsorption characteristics of the metals–sediment mixture and the effects of flow characteristics within the model detention basin were examined. Metal (lead, cadmium, copper, and zinc) adsorption characteristics were defined using batch equilibrium adsorption techniques, coagulant screening for applicability to system specific conditions unique to stormwater detention basins

was evaluated using jar tests, and the impact of flow on contaminant removal was defined through the application of scale model studies.

Data collected in this study confirmed that the smaller size fraction particles contain the majority of adsorbed metals, particularly lead and copper. Significant improvement in metal removal was realized through the addition of coagulants ($FeCl_3 \cdot 6H_2O$ or SWT 848, a cationic inorganic polymer). These coagulants served to increase removal of the small sediment size fraction and, as a result, metal removal was improved. Specific findings are summarized in the following statements.

- The literature review indicated large variation in highway stormwater quality. The decision making process regarding the implementation of enhanced contaminant removal practices should include an evaluation of water quality for the detention basin(s) being considered. If water quality is determined to be acceptable relative to the receiving water, no action would be necessary.

- A modified jar test procedure is required to adequately evaluate coagulants for storm detention basin application. The procedure involves using a relatively short flash mix period (simulating the detention time from the point of addition to the basin), followed by a non-mixed settling period with a duration equivalent to the average basin hydraulic detention time. This procedure was found to yield jar test results that were more representative of coagulant action during scale model tests.

- Over the range of flow rates studied, metal removal varied from approximately 0 percent to 35 percent with no coagulant addition and 35 percent to 78 percent with coagulant addition. These removals are in contrast to observed sediment removal without coagulant addition that ranged from 60 to 75 percent, indicating the importance of removing the smallest size fractions when maximum contaminant removal is desired.

- Further enhancement (10 to 20 percent) in metal removal at the highest flow rate was realized by the addition of an influent flow baffle. The need for an influent flow baffle would be site specific and could be assessed by performing inert tracer experiments.

- Coagulant addition has been shown to significantly improve the effectiveness of stormwater detention basins with respect to contaminant removal. Coagulant selection and concentration of optimum performance would require preliminary jar test studies. These studies should be performed on stormwater collected from the site during storm events.

- General criteria that should be considered when evaluating coagulants for field application include:
    - ◊ wide window of operation (effective over a broad range of concentration and pH)
    - ◊ rapid rate of flocculation
    - ◊ low levels of sludge production
    - ◊ acceptable for use in drinking water treatment applications to prevent toxicity concerns

- Optimum dose of SWT 848 was $\geq$ 50 ppmv (parts per million by volume) and $FeCl_3 \cdot 6H_2O$ was 15 to 25 mg/L as Fe.

Chemical cost for a "typical" storm event was estimated by applying storm event information for a particular region of interest. For example, using a Type 1A storm event in the Olympia, Washington area, the runoff volume from 1000 ft. of four lane highway is approximately 50,000 gal. (1.79 in. total rainfall). Assuming that the coagulant dosage defined by this research is applicable to the field stormwater, the storm event would require 2.5 gal. of SWT 848 at a 50 ppmv application. Chemical cost for the entire storm event would be approximately $15 ($6/gal.). It should be noted that chemical cost savings and lower sludge production rates would be realized by treating a portion of each storm event. Decisions regarding this treatment strategy would be dependent upon the stormwater character at each site.

# INTRODUCTION AND LITERATURE REVIEW

## Research Objectives

The overall goal of this project was to determine if existing detention basins could be utilized as an effective means of removing contaminants from highway runoff. This goal was realized by meeting the following specific project objectives.

- Assess a variety of coagulants for their ability to enhance contaminant removal in stormwater detention basins
- Perform scale model testing on selected coagulants to determine optimum dose over a range of flow rates.
- Quantify contaminant removal efficiency as a function of flow and coagulant type.
- Assess the impact of enhancing basin hydraulics on contaminant removal.

Limiting highway-borne contaminant loads to receiving waters is a high priority of the WSDOT. Detention basins often remove only the larger size fractions of sediments found in highway runoff, consequently removing only a small percentage of heavy metals. This project evaluates the effectiveness of coagulants as a mechanism for removing fine sediment fractions and associated heavy metals in highway runoff. Bench scale experiments were designed to evaluate the ability of various coagulants to remove contaminants in a simulated highway runoff. Coagulant doses were optimized with respect to contaminant removal in jar test experiments, after which the coagulant was introduced to the simulated highway runoff in a scale model detention basin. Four surface overflow rates (the ratio of flow rate to surface area) was applied to the model detention basin, and coagulant dosage were further optimized with respect to surface overflow rate (SOR) and contaminant removal.

Contaminants in highway runoff can have deleterious impacts on receiving waters. Portele, *et al*. report adverse effects of soluble fractions of contaminants on zooplankton and algae, while suspended solids cause high mortality of rainbow trout fry (Portele *et al*., 1982). Another study reports elevated lead concentrations in barn swallows nesting adjacent to highways (Grue *et al*., 1984). Washington State Department of Ecology has declared that limiting highway borne contaminants a high priority (Washington Department of Ecology, 1992). In response to known and suspected impacts of highway runoff on receiving waters, the Washington State Department of Transportation (WSDOT) has been involved in stormwater quality monitoring and control since the 1970's.

Studies aimed at quantifying highway runoff characteristics and determining best management practices have found that grassy swales, wetlands, retention/infiltration basins, and dual purpose detention basins could be effectively used for removing a variety of stormwater contaminants under certain system conditions and receiving water constraints (Pittman, 1991; Taylor, 1991; Yousef *et al*., 1985; Yousef *et al*., 1991). Generally, grassy swales and wetlands provided the highest degree of treatment. The most common management practice, however, is dual purpose detention basins, initially constructed as flood control devices. These basins were designed to store a portion of a storm event and then release that water over an extended time period. Although flood control was the primary application, most detention basins exhibited an ability to remove particulate matter, as evidenced by the need to periodically remove accumulated sediments. In most cases however, their sediment removal efficiency has not been quantified, and as a result, rational design information is unavailable.

Cole and Yonge (1993), through scale model testing, determined that discrete particle settling theory can be used to estimate sediment removal in stormwater detention basins.

Sediment removal efficiencies ranged from 65% to 80% as a function of flow and model basin inlet/outlet configurations. Theoretical model predictions were within 7% of measured sediment removal values. Preliminary tests indicated that metal removal ranged from 28% to 40%, significantly less than observed sediment removal values. It was determined that this was a direct result of the inverse relationship between metal partitioning and sediment size (Amy *et al*., 1974; Hopke et al., 1980; Cole and Yonge, 1993; Shaheen, 1975; Svensson, 1987). Thus, it appears that smaller particles contain more adsorbed metal species than larger particles, and, due to their small size (and subsequently lower settling velocities), are only partially removed in a detention basin. Similar contaminant removal results were observed which show that the failure to remove small particulate matter would prevent achievement of target discharge concentrations for certain contaminants (Hvitved–Jacobsen and Yousef, 1991). Based on these results, it is apparent that enhanced metals removal could be accomplished by increasing the removal of the smaller sediment size fraction.

Increased stormwater sediment capture efficiency can be realized through a decrease in surface overflow rate (SOR), where SOR is the ratio of basin influent flow to basin surface area (Metcalf and Eddy, 1991). This could be accomplished through flow reduction and/or an increase in basin surface area. The modifications necessary to decrease SOR in existing detention basins, however, may be cost prohibitive, or there may be physical constraints, such as space availability, that prevent implementation. One method of increasing removal of sediment and associated contaminants without physical basin modification is through the application of chemical coagulants to the stormwater influent. Chemical coagulation is a common practice in water and wastewater treatment applications and would be effective in some detention basin systems. Enhanced sediment removal results from an apparent increase in particle size through

3

particle charge neutralization and particle–particle bridging (referred to as floc formation) to form aggregates of the smaller particles (floc). The larger aggregates have higher terminal settling velocities, resulting in increased particle removal at a given SOR. This paper presents results illustrating the effects of coagulant addition in a scale model detention basin to simulated stormwater during scale model storm events.

## EXPERIMENTAL METHODS

### Development of Simulated Stormwater

Table 1 summarizes the constituents and their concentrations used in the simulated stormwater (SSW). These concentrations were selected based on literature values of national averages and, as such, represent a "typical" highway runoff (Barrett and Zuber et al., 1993).

**TABLE 1  Simulated Stormwater Constituents and Their Target Concentrations**

| Parameter | Concentration (mg L$^{-1}$) |
| --- | --- |
| Suspended Solids | 500 |
| Lead | 1.8 |
| Cadmium | 0.06 |
| Copper | 0.18 |
| Zinc | 1.3 |

The sediment used in the SSW was obtained from Wallowa lake in eastern Oregon. The sediment at this site was selected for its minimal indigenous heavy metal concentrations, since there is no road access upstream of the lake, and thus, little likelihood of contamination by automobile pollutants. The sediment was transported to the laboratory and stockpiled on a tarp at

a depth of approximately 0.15 m and air dried at ambient temperatures (approximately 20 °C) for several weeks. The soil was undisturbed during drying to minimize unintentional stratification. The dried sediment was shaken on a US Standard #28 sieve (0.625 mm mesh size) using a Soiltest hammer–type shaker for 15 minutes to remove larger size fractions and unwanted debris. The fraction passing through the #28 sieve was then ground on a Cincinnati muller–type grinder for 30 minutes to reduce the sediment to elementary particles. After grinding, the soil was shaken in a sieve stack for 30 minutes and all sediment that had passed the #200 sieve (0.075 mm) was used for preparing the SSW. Hydrometer analysis (ASTM D–422) was then performed to define the particle size distribution of the sediments.

**Bench Scale Evaluation**

Four coagulants, $Al_2(SO_4)_3 \cdot 18H_2O$, $FeCl_3 \cdot 6H_2O$, and two cationic inorganic coagulants (SWT 848 and SWT 976, Southern Water Treatment Co., Greenville, SC) were evaluated in bench scale, jar test experiments. Evaluation included qualitative (supernatant clarity and floc settleability) and quantitative assessment (metals removal, sediment removal, and rate of floc formation). Two jar test procedures were performed. The first procedure followed ASTM specifications (e.g., 1 minute rapid mix, 20 minute slow mix, 30 minute settling period) while the second procedure included modifications designed to more closely simulate initial mixing and contact times in the model detention basin (0.5 minute rapid mix, no slow mix, 4–11 minute settling period). Variable settling periods afforded a means of evaluating coagulant effectiveness in terms floc formation potential within the hydraulic detention time of the basin.

**Model Detention Basin Experiments**

The 1:15 scale model constructed as part of this project replicates an existing detention basin located on the NE corner of the Henderson Blvd. interchange on I-5 in Olympia, Washington. This basin was selected as the basis for scale model development because it was representative of several basins in the area. An initial field survey of the basin was performed and the resulting basin dimension data used to design experimental parameters for scale model construction and testing.

Scale Model Design and Construction

The scale factor for the model was determined by applying sedimentation theory of descrete particles (Type I sedimentation theory) that is known to be valid in sedimentation basins. Removal of particles exhibiting Type I sedimentation is a function of surface overflow rate (SOR) only, which is defined in equation 1.

$$SOR = \frac{Q}{A} \tag{1}$$

where
$Q$ = flow ($m^3/s$)
$A$ = surface area ($m^2$)

Since sediment removal is based on SOR, the model and field SORs can be set equal to one another. Manipulation of equation 2 resulted in the relationships presented in equations 3 - 5. It can be seen that for a 1:15 scale, field and model flow is related by the scale factor 225 ($15^2$).

Field flow was estimated based on maximum sustained flow that the basin could maintain without over-topping the berm. This flow would result in a worst case scenario with respect to contaminant removal. Information from a field survey yielded data (effluent pipe length, pipe

type, slope, and hydrostatic head) required for application of Manning's equation for closed-conduit flow.  The flow corresponding to such a condition was calculated to be approximately . Equation   was then applied to determine the maximum scale model flow.  Other lower flows were selected, resulting in a total of four flows that were used during scale model testing.

Scale model flow rate, liquid surface area, and the resulting surface overflow rates are listed in Table 2.  Surface overflow rate (SOR) is defined in equation 1.  The data in column two indicate that the liquid surface area of the basin decreases as flow decreases.  This is a result of the steady state water level decreasing at lower flow rates, resulting in lower estimated surface area.

**Table 2.**  Liquid surface area, scale model flow, and corresponding surface overflow rate for the scale model.

| Surface Overflow rate [μm/s] | Surface area of model[$m^2$] | Flow rate [L/min]/[gpm] |
|---|---|---|
| 302 | 2.51 | 45.42/12 |
| 242 | 2.33 | 34.07/9 |
| 205 | 2.16 | 26.50/7 |
| 145 | 2.14 | 18.93/5 |

Figure 1 is a schematic representation of the model detention basin experimental apparatus. A concentrated (approximately 32 times the basin influent concentration) contaminant slurry was completely–mixed in a 115 L Nalgene tank. Use of a concentrated slurry was necessary because of the logistical difficulty required to prepare and maintain a well–mixed SSW at target concentrations in a much larger tank. The slurry solution was blended with tap water from a 3,800 L feed tank in a 12 L completely–mixed blend tank. This served to dilute the slurry to target contaminant concentration values (Table 1). In addition, coagulant was metered into the 12L blend tank for those experiments involving coagulant addition. All flows were

controlled by variable speed peristaltic pumps. Flow rate was calibrated prior to each experiment and measured at its completion. Triplicate runs were performed at one flow rate and a constant coagulant dosage to define experimental error.
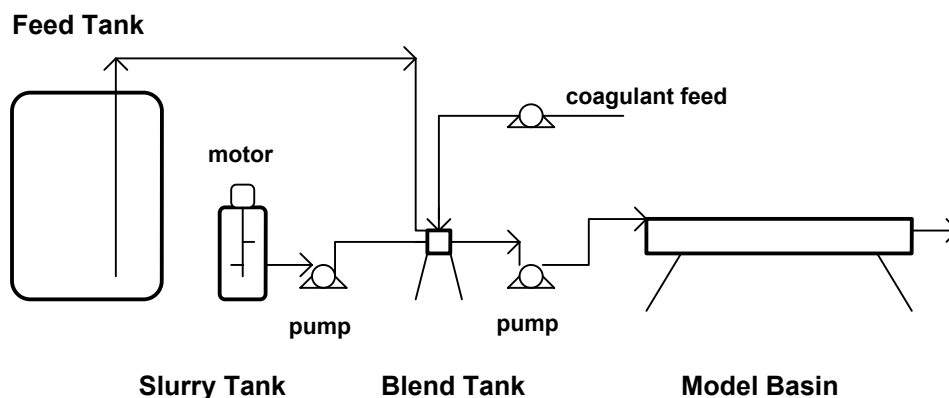


**FIGURE 1**  Schematic Representation of Model Basin Experimental Apparatus

**Tracer Study**

Conservative tracer experiments were performed to investigate the hydraulic response of the basin to the installation of an inlet baffle. The baffle was placed perpendicular to the direction of flow, 46 cm from the point where the inlet flow stream entered the basin pool. A pulse input of NaCl was injected in the influent flow stream of the basin and effluent specific conductance was monitored as a function of time to define the tracer response profile. The baffle conformed to the bottom profile of the basin and was constructed from 0.64 cm thick Plexiglas sheet. Holes (1 cm diameter, uniformly spaced at 4 cm on center) were drilled through the baffle to obtain a more evenly distributed velocity profile over the basin cross–section.

**Metals Partitioning**

Characterization of metal sorption as a function of soil particle size was achieved in a bench–scale settling column experiment. The sediment was equilibrated with the metals at slurry tank concentrations for 24 hours. Two liters of the equilibrated soil slurry were placed in each of five 2 L graduated cylinders. Samples were collected from a fixed location (15 cm from the top of the cylinder) at predetermined time intervals. These samples were analyzed for total metal, soluble metal, and suspended solids concentrations. Adsorbed metal concentrations were determined by difference. Each sample was also characterized with respect to mean particle size using a particle size distribution analyzer (Horiba CAPA–700).

## FINDINGS AND INTERPRETATION

**Jar Test**

The four coagulants investigated exhibited some ability to remove suspended solids (measured as turbidity) under standard ASTM jar test protocol. SWT 976 performed as well but not better than SWT 848, and as a result was not used in model basin experiments. However, the modified jar test procedure indicated that $Al_2(SO_4)_3 \cdot 18H_2O$ was ineffective at destabilizing the sediment suspension and initiating floc formation in the relatively short rapid–mixing period. As a result, it was not used in the model basin experiments. Conversely, $FeCl_3 \cdot 6H_2O$ and SWT 848 performed well, exhibiting rapid floc formation and good solids settling characteristics.

The optimum dosage for $FeCl_3 \cdot 6H_2O$, based on sediment and metals removal, was 15 mg/l as Fe. It was noted that the optimum fell in a narrow range; concentrations 15% less or greater resulted in a significant deterioration in performance. Suspended solids and metal removal using SWT 848 were found to be much less sensitive to dosage once a minimum

threshold value of 50 mL/L was achieved, offering a wide range of operational control. This characteristic is important when considering highway stormwater detention system design. The high number of basins to maintain and their non-ideal access requires a simple, low maintenance method of coagulant application. A coagulant that performed effectively over a broad concentration range would be preferred in such systems.

**Metals Partitioning**

The data in Figure 2 describes the influence of sediment particle size on sorption capacity. Sorption of zinc exhibited the least sensitivity to particle size of the four metals, and is shown to be adsorbed approximately 4.7 times greater to particles of 4 μm (average approximate spherical diameter) than to 17 μm particles. Lead, representative of metals having stronger sorption characteristics, exhibits a 4 μm particle sorption capacity that is approximately 6 times greater than that for 17 μm particles. The relationship presented in Figure 1 indicates that increases in detention basin contaminant removal can be achieved by increasing removal of the smallest particles.

**Model Basin Performance**

Several preliminary basin experiments were performed to define optimum coagulant dose with respect to metal removal for $FeCl_3 \cdot 6H_2O$ and SWT 848. These tests indicated that $FeCl_3 \cdot 6H_2O$ was sensitive to dose, requiring dose optimization for each of the four test flow rates. Conversely, SWT 848 did not exhibit dose sensitivity over the range of flow rates studied, confirming the results of the jar test experiments.

The metals removal data in Figure 3a–d show the influence of coagulant addition upon metal removal over the range of SOR's studied. Two general trends are apparent: (i) metal removal is inversely proportional to SOR and (ii) coagulant addition results in a statistically significant (at a 95% confidence level) improvement in contaminant removal. Additionally, it can be seen that SWT 848 performed as well or better than $FeCl_3 \cdot 6H_2O$.
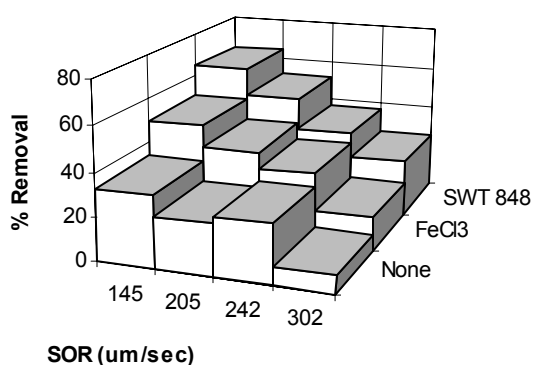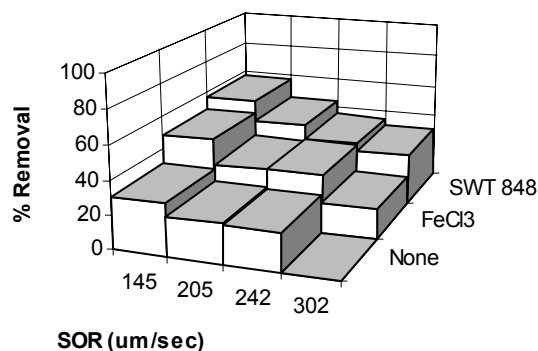


(a)                                                    (b)
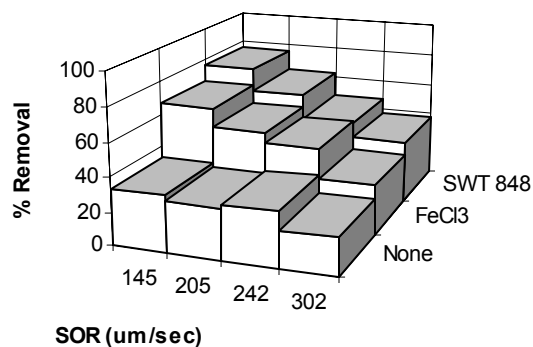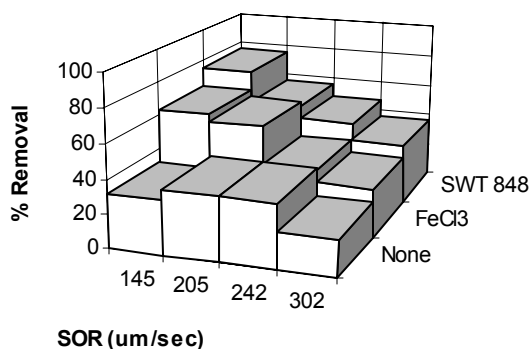
(c)                                                                (d)

**FIGURE 3** Effect of flow and coagulant addition on metals removal. (a) Zinc. (b) Cadmium. (c) Lead. (d) Copper.

Sediment removal data (Figure 4) also exhibit the inverse relationship between flow rate and removal. However, coagulant addition appears to decrease solids removal. This anomaly is likely a result of the influence of the coagulant on the suspended solids analysis procedure. Some of the coagulant was retained on the filter from the suspended solids sample, even after thorough rinsing (by filtering deionized water) and drying at 104 °C; thus, measured solids concentrations incorporate the weights of both the sediment and coagulant retained on the filter. Since floc formation is time dependent, more aggregated coagulant was measured in the effluent samples than in the influent samples, giving the appearance of decreasing solids removal, when sediment removal was actually enhanced, as evidenced by the improved metal removal data and the known inverse relationship between particle size and metal adsorption.
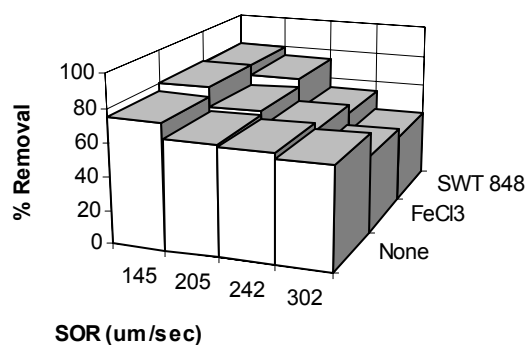
**FIGURE 4**  Effect of Flow and Coagulant Addition on Suspended Solids Removal

Further enhancement of contaminant removal was evaluated by modifying basin hydraulics by the insertion of a baffle. Experiments were performed during coagulant addition (SWT 848) to assess baffle influence on contaminant removal. The data in Figure 5a–d show significant improvement in removal at the two highest SOR's (242 μm/sec and 302 μm/sec) for all metals. This is a result of an improvement in basin hydraulics which reduced basin short–circuiting and an increased solids and adsorbed metal capture.



(a)



(b)
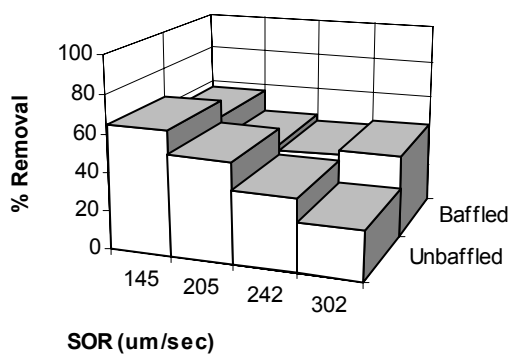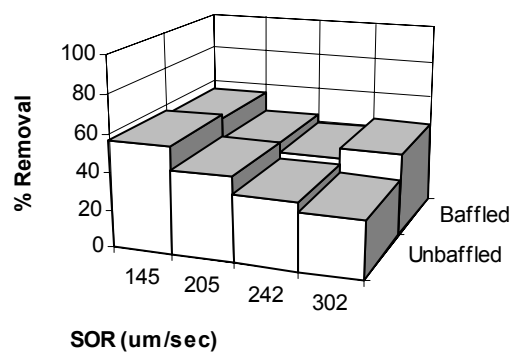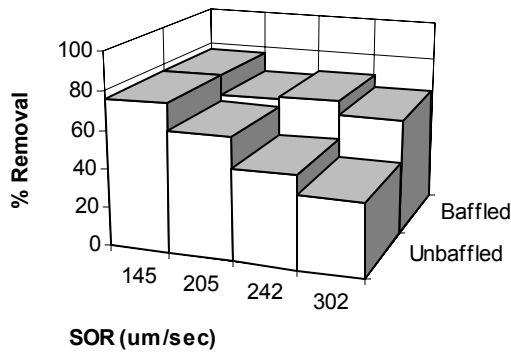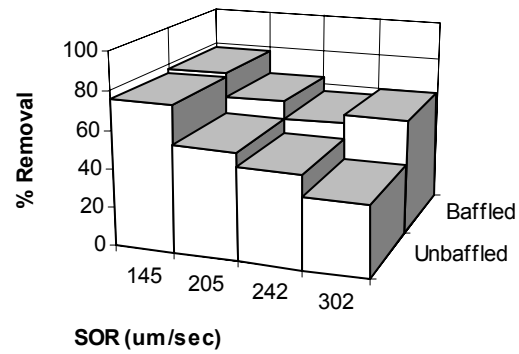
FIGURE 5  Effect of baffling on metals removal during coagulation by SWT 848.
(a) Zinc. (b) Cadmium. (c) Lead. (d) Copper.

Improved basin hydraulics, following baffle placement, can be observed in the tracer response profiles plotted in Figure 6. It can be seen that the maximum tracer concentration was recorded at 0.7 min for the unbaffled condition. This response profile indicates that significant short–circuiting is occurring when a comparison is made to the theoretical basin detention time of 5.5 min. Baffle installation results in a shift of the maximum tracer concentration to 2.2 min, indicating a significant reduction in short–circuiting. Therefore, the observed improvement in contaminant removal at the higher SOR's using a baffled system is likely the result of an improvement in the residence time distribution. This results in a more uniform flow distribution through the system, improving floc formation and sediment removal efficiency.
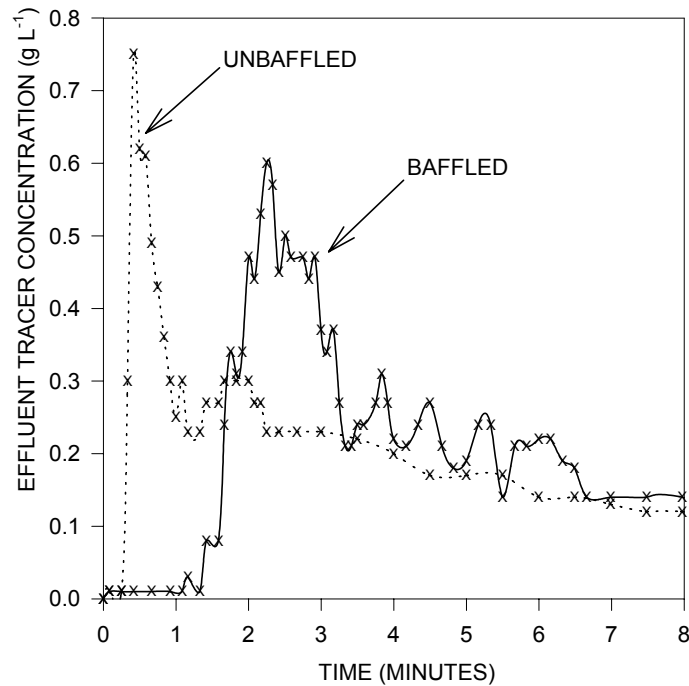
**FIGURE 6**  Conservative Tracer Response Profile (SOR = 302 μm/sec)

## CONCLUSIONS AND RECOMMENDATIONS

Results of the scale model detention basin testing indicate that significant improvement

in contaminant removal can be obtained by the addition of chemical coagulants.  This

improvement was a result of enhanced removal of smaller sediment size fraction and those

metals adsorbed to that size fraction.  For example, over the range of flows studied, sediment

removal (without coagulant addition) varied from approximately 60% to 75% while lead

removal varied from 15% to 35%.  Coagulant addition resulted in lead removals of 38% to 77%,

an average increase in removal of 135%.

Of the four coagulants studied, ferric chloride and SWT 848 resulted in the best overall performance while alum and SWT 976 were found to be ineffective. It was concluded that coagulant effectiveness with regard to contaminant removal was primarily dependent upon rate of floc formation. This attribute would be important under field application conditions where the coagulant would be added in the influent flow stream (e.g., a culvert or ditch). Under this condition, the coagulant would have to induce coagulation in a short time period. In addition, to afford unattended operation, the coagulant should be effective over a wide concentration and pH range.

Preliminary coagulant screening should be carried out with stormwater samples collected in the field that cover a range of anticipated water quality conditions. A modified jar test procedure was developed and should be used during the screening procedure as this will afford results that are representative of anticipated field conditions. The procedure was developed to simulate the conditions in the scale model and consisted of:

- 0.5 minute rapid mix,
- 4–11 minute settling period with no mixing.

Variable settling periods afforded a means of evaluating coagulant effectiveness in terms floc formation potential within the hydraulic detention time of the basin.

This procedure should be modified, as necessary, to mimic the conditions for a particular detention basin system. For example, if there is a one minute detention time from the point of coagulant addition to the detention basin and a 10 minute average hydraulic detention time in the basin then the jar test conditions should be rapid mix for one minute followed by ten minute settling period. Supernatant would then be collected for testing. This testing would be most

efficiently carried out by measuring turbidity during the initial screening procedure. If more detailed information is desired, samples could be analyzed for specific contaminants of interest.

The importance of basin hydraulics in contaminant removal efficiency was made evident by the placement of an influent baffle that more evenly distributed the flow across the cross section of the basin, reducing hydraulic short circuiting and increasing contaminant removal. If flow hydraulics are not obvious from a detention basin field survey, a conservative tracer experiment should be performed to estimate the degree of short circuiting. If it is determined that basin hydraulics should be improved, a field scale influent flow device would be relatively inexpensive to fabricate and install.

Treatment of a storm event can be achieved by two separate methods treatment of an entire storm event or treatment of the "first flush". First flush treatment is based on time dependent fluctuations in storm water characteristics. A drainage which exhibits a first flush characteristic may contain 80% of the total contaminant load in the first 20% of the total stormwater volume. However, measurement of critical runoff constituents with respect to time during a storm event may allow for the determination of a site specific first flush volume. If first flush treatment is determined to be appropriate for a given drainage, coagulant cost savings and lower sludge production are the expected advantages.

Chemical cost for a "typical" storm event can be estimated by applying storm event information for a particular region of interest. For example, using a Type 1A storm event in the Olympia, Washington area, the runoff volume from 1000 ft. of four lane highway is approximately 50,000 gal. (1.79 in. total rainfall). Assuming that the coagulant dosage defined by this research is applicable to the field stormwater, the storm event would require 2.5 gal. of SWT 848 at a 50 ppmv application. Chemical cost for the entire storm event would be

approximately $15 ($6/gal.). It should be noted that chemical cost savings and lower sludge

production rates would be realized by treating a portion of each storm event. Decisions

regarding this treatment strategy would be dependent upon the stormwater character at each site.

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**APPENDIX**


**Data from Experimental Runs**

| Symbol | Description |
|---|---|
| SS | dry weight suspended solids |
| SOR | surface overflow rate (surface area/flow) |
| REM | Percent removal (1-mass out/mass in)*100 |
| IN | model basin influent concentration |
| OUT | model basin effluent concentration |
| TM | total metal concentration (liquid + solid phase) |
| LM | liquid metal concentration |
| L | length |
| Rc | corrected reading |
|  |  |
|  |  |
|  |  |

Table A1.  Suspended solids and metal removal for scale model basin experiments

| SOR (um/sec) | COAGULANT TYPE | DOSE (mg/l or ppmv) | BAFFLE | SS IN (mg/l) | SS OUT (mg/l) | SS REM | Pb TM IN (mg/l) | Pb TM OUT (mg/l) | Pb TM REM | Pb LM IN (ug/l) | Pb LM OUT (ug/l) | Pb LM REM | Cd TM IN (ug/l) | Cd TM OUT (ug/l) | Cd TM REM | Cd LM IN (ug/l) | Cd LM OUT (ug/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 145 | NONE | 0 | n | 508 | 143 | 72 | 2.0 | 1.5 | 24 | 110 | 103 | 6 | 61 | 45 | 26 | 14 | 14 |
| 145 | NONE | 0 | n | 582 | 133 | 77 | 2.0 | 1.2 | 43 | 20 | 15 | 28 | 49 | 32 | 36 | 20 | 16 |
| 145 | IRON | 5 | n | 668 | 184 | 73 | 2.7 | 1.6 | 42 | 13 | 12 | 5 | 79 | 48 | 39 | 15 | 13 |
| 145 | IRON | 8 | n | 555 | 109 | 80 | 1.8 | 0.6 | 66 | | | | 49 | 25 | 49 | 13 | 11 |
| 145 | IRON | 10 | n | 448 | 104 | 77 | 2.1 | 0.8 | 64 | | | | 58 | 43 | 26 | 22 | 20 |
| 145 | IRON | 15 | n | 539 | 103 | 81 | 2.4 | 0.7 | 69 | 34 | 19 | 43 | 67 | 44 | 34 | 28 | 25 |
| 145 | IRON | 15 | n | 587 | 103 | 82 | 2.1 | 0.6 | 70 | | | | 50 | 22 | 55 | 19 | 12 |
| 145 | IRON | 25 | n | 555 | 149 | 73 | 1.7 | 0.5 | 71 | | | | 46 | 24 | 47 | 17 | 14 |
| 145 | IRON | 25 | n | 509 | 74 | 85 | 2.2 | 0.5 | 79 | | | | 59 | 37 | 38 | 27 | 25 |
| 145 | SWT 848 | 100 | n | 532 | 115 | 78 | 1.9 | 0.5 | 72 | | | | 58 | 27 | 54 | 10 | 8 |
| 145 | SWT 848 | 100 | n | 440 | 83 | 81 | 2.0 | 0.4 | 80 | | | | 59 | 24 | 60 | 14 | 14 |
| 145 | SWT 848 | 100 | y | 624 | 112 | 82 | 2.5 | 0.6 | 76 | | | | 69 | 31 | 55 | 15 | 8 |
| 205 | NONE | 0 | n | 522 | 187 | 64 | 2.1 | 1.5 | 29 | 72 | 53 | 27 | 69 | 53 | 23 | 26 | 23 |
| 205 | NONE | 0 | n | 478 | 160 | 67 | 1.9 | 1.3 | 31 | 66 | 61 | 7 | 59 | 45 | 24 | 26 | 15 |
| 205 | IRON | 8 | n | 504 | 162 | 68 | 2.0 | 1.0 | 48 | | | | 62 | 47 | 24 | 20 | 16 |
| 205 | IRON | 8.5 | n | 458 | 131 | 71 | 2.1 | 1.1 | 46 | 22 | 30 | -38 | 62 | 44 | 30 | 19 | 15 |
| 205 | IRON | 11 | n | 490 | 166 | 66 | 1.7 | 0.8 | 52 | | | | 56 | 38 | 33 | 11 | 6 |
| 205 | IRON | 16 | n | 580 | 188 | 68 | 2.3 | 1.0 | 55 | 49 | 22 | 55 | 66 | 43 | 34 | 5 | 6 |
| 205 | SWT 848 | 50 | n | 582 | 173 | 70 | 2.3 | 1.1 | 55 | | | | 71 | 42 | 41 | 16 | 15 |
| 205 | SWT 848 | 100 | n | 565 | 165 | 71 | 2.2 | 0.9 | 59 | | | | 65 | 40 | 38 | 13 | 8 |
| 205 | SWT 848 | 100 | n | 675 | 160 | 76 | 2.4 | 0.8 | 66 | | | | 76 | 38 | 50 | 19 | 15 |
| 205 | SWT 848 | 100 | y | 563 | 146 | 74 | 2.3 | 0.8 | 66 | | | | 64 | 36 | 44 | 15 | 7 |
| 242 | NONE | 0 | n | 511 | 182 | 64 | 2.0 | 1.4 | 30 | 64 | 40 | 38 | 67 | 56 | 16 | 25 | 22 |
| 242 | NONE | 0 | n | 466 | 172 | 63 | 1.7 | 1.1 | 34 | 69 | 46 | 33 | 57 | 41 | 28 | 26 | 22 |
| 242 | IRON | 7 | n | 354 | 150 | 58 | 1.5 | 1.0 | 34 | 30 | 10 | 67 | 47 | 39 | 17 | 14 | 13 |
| 242 | IRON | 8 | n | 471 | 193 | 59 | 2.1 | 1.4 | 31 | | | | 61 | 48 | 22 | 20 | 15 |
| 242 | IRON | 8 | n | 517 | 217 | 58 | 1.9 | 1.2 | 38 | | | | 70 | 54 | 23 | 20 | 17 |
| 242 | IRON | 10.5 | n | 530 | 218 | 59 | 2.1 | 1.1 | 48 | | | | 68 | 45 | 35 | 16 | 16 |
| 242 | IRON | 20 | n | 464 | 225 | 52 | 2.0 | 1.2 | 43 | 31 | 14 | 55 | 58 | 41 | 30 | 5 | 7 |
| 242 | SWT 848 | 100 | n | 571 | 265 | 54 | 2.1 | 1.1 | 47 | | | | 63 | 41 | 35 | 10 | 5 |
| 242 | SWT 848 | 100 | y | 573 | 184 | 68 | 2.3 | 1.0 | 58 | | | | 66 | 40 | 39 | 12 | 5 |
| 302 | NONE | 0 | n | 444 | 176 | 60 | 1.8 | 1.4 | 22 | 53 | 45 | 15 | 57 | 60 | -5 | 28 | 29 |
| 302 | IRON | 10 | n | 456 | 225 | 51 | 1.9 | 1.4 | 29 | | | | 60 | 54 | 10 | 24 | 20 |
| 302 | IRON | 25 | n | 556 | 300 | 46 | 2.3 | 1.6 | 30 | | | | 69 | 57 | 17 | 29 | 26 |
| 302 | SWT 848 | 100 | y | 615 | 199 | 68 | 2.6 | 1.0 | 61 | | | | 70 | 39 | 44 | 15 | 9 |
| 302 | SWT 848 | 100 | n | 453 | 267 | 41 | 2.0 | 1.2 | 38 | | | | 53 | 37 | 31 | 15 | 8 |

**Table A1 (cont.)**

| SOR (um/sec) | COAGULANT TYPE | DOSE (mg/l or ppmv) | BAFFLE | Cu TM IN (ug/l) | Cu TM OUT (ug/l) | Cu TM REM | Cu LM IN (ug/l) | Cu LM OUT (ug/l) | Cu LM REM | Zn TM IN (mg/l) | Zn TM OUT (mg/l) | Zn TM REM | Zn LM IN (mg/l) | Zn LM OUT (mg/l) | Zn LM REM | Fe TM IN (mg/l) | Fe TM OUT (mg/l) | Fe TM REM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 145 | NONE | 0 | n | 280 | 184 | 34 | 20 | 16 | 21 | 1.7 | 1.2 | 29 | | | | 4.8 | 2.7 | 44 |
| 145 | NONE | 0 | n | 183 | 132 | 28 | 19 | 6 | 67 | 1.5 | 1.0 | 37 | 0.4 | 0.3 | 11 | 2.3 | 1.3 | 45 |
| 145 | IRON | 5 | n | 369 | 180 | 51 | 7 | 7 | 0 | 2.3 | 1.2 | 45 | | | | 9.7 | 6.5 | 33 |
| 145 | IRON | 8 | n | 192 | 70 | 63 | 7 | 8 | -22 | 1.3 | 0.6 | 50 | 0.3 | 0.3 | 24 | 11.3 | 7.0 | 38 |
| 145 | IRON | 10 | n | 261 | 97 | 63 | 6 | 8 | -50 | 1.6 | 1.2 | 27 | 0.8 | 0.6 | 25 | 14.5 | 8.2 | 44 |
| 145 | IRON | 15 | n | 296 | 88 | 70 | 17 | 14 | 20 | 1.7 | 1.2 | 30 | 0.9 | 0.9 | 9 | 19.4 | 9.5 | 51 |
| 145 | IRON | 15 | n | 169 | 64 | 62 | 7 | 10 | -45 | 1.4 | 0.6 | 57 | 0.4 | 0.3 | 29 | 18.5 | 8.4 | 55 |
| 145 | IRON | 25 | n | 195 | 68 | 65 | 8 | 5 | 34 | 1.2 | 0.7 | 44 | 0.5 | 0.4 | 15 | 29.5 | | |
| 145 | IRON | 25 | n | 274 | 77 | 72 | 3 | 3 | 10 | 1.7 | 1.1 | 34 | 0.9 | 0.8 | 9 | 29.0 | 11.2 | 61 |
| 145 | SWT 848 | 100 | n | 185 | 53 | 72 | 3 | 7 | -108 | 1.7 | 0.6 | 62 | 0.1 | 0.1 | 0 | | | |
| 145 | SWT 848 | 100 | n | 195 | 40 | 79 | 4 | 2 | 34 | 1.6 | 0.5 | 67 | 0.1 | 0.1 | 0 | | | |
| 145 | SWT 848 | 100 | y | 263 | 59 | 77 | 6 | 3 | 56 | 1.9 | 0.9 | 55 | 0.2 | 0.1 | 58 | | | |
| 205 | NONE | 0 | n | 287 | 177 | 38 | 15 | 12 | 22 | 1.5 | 1.2 | 23 | 0.3 | 0.3 | 12 | 4.0 | 2.6 | 35 |
| 205 | NONE | 0 | n | 240 | 149 | 38 | 18 | 15 | 17 | 1.6 | 1.2 | 23 | 0.5 | 0.5 | 12 | 4.7 | 2.6 | 45 |
| 205 | IRON | 8 | n | 271 | 138 | 49 | 7 | 4 | 33 | 1.7 | 1.2 | 30 | 0.5 | 0.3 | 24 | 13.1 | 8.4 | 36 |
| 205 | IRON | 8.5 | n | 220 | 117 | 47 | 10 | 10 | -6 | 1.7 | 1.2 | 32 | 0.3 | 0.2 | 33 | 13.2 | 8.3 | 38 |
| 205 | IRON | 11 | n | 233 | 128 | 45 | 8 | 5 | 35 | 1.7 | 1.1 | 37 | 0.2 | 0.3 | -50 | 15.8 | 10.1 | 36 |
| 205 | IRON | 16 | n | 293 | 120 | 59 | 12 | 8 | 31 | 1.9 | 1.2 | 40 | 0.1 | 0.1 | 0 | 20.1 | 12.0 | 40 |
| 205 | SWT 848 | 50 | n | 500 | 367 | 26 | 6 | 5 | 26 | 1.9 | 0.9 | 50 | 0.0 | 0.0 | 0 | | | |
| 205 | SWT 848 | 100 | n | 288 | 106 | 63 | | | | 1.8 | 1.0 | 46 | 0.1 | 0.1 | 36 | | | |
| 205 | SWT 848 | 100 | n | 526 | 275 | 48 | 9 | 5 | 40 | 2.0 | 0.8 | 58 | 0.1 | 0.0 | 50 | | | |
| 205 | SWT 848 | 100 | y | 247 | 87 | 65 | 2 | 4 | -68 | 1.8 | 1.0 | 44 | 0.2 | 0.1 | 60 | | | |
| 242 | NONE | 0 | n | 277 | 171 | 38 | 20 | 13 | 37 | 1.6 | 1.2 | 25 | 0.3 | 0.3 | 26 | 4.0 | 2.7 | 31 |
| 242 | NONE | 0 | n | 226 | 143 | 37 | 18 | 28 | -58 | 1.5 | 1.1 | 28 | 0.5 | 0.3 | 37 | 3.7 | 2.2 | 41 |
| 242 | IRON | 7 | n | 151 | 106 | 30 | 8 | 7 | 13 | 1.3 | 1.0 | 17 | 0.2 | 0.2 | 0 | 11.1 | 7.5 | 33 |
| 242 | IRON | 8 | n | 239 | 160 | 33 | 10 | 7 | 25 | 1.6 | 1.3 | 19 | 0.3 | 0.2 | 47 | 12.8 | 9.1 | 29 |
| 242 | IRON | 8 | n | 297 | 159 | 47 | 9 | 9 | -6 | 1.7 | 1.3 | 23 | 0.4 | 0.4 | 16 | 12.6 | 8.3 | 35 |
| 242 | IRON | 11 | n | 256 | 163 | 36 | 5 | 13 | -168 | 1.8 | 1.2 | 32 | 0.2 | 0.5 | -104 | 15.5 | 10.0 | 36 |
| 242 | IRON | 20 | n | 260 | 145 | 44 | 7 | 5 | 30 | 1.6 | 1.2 | 29 | 0.1 | 0.2 | -100 | 24.3 | 14.6 | 40 |
| 242 | SWT 848 | 100 | n | 213 | 111 | 48 | 3 | 3 | 7 | 1.8 | 1.1 | 38 | 0.1 | 0.0 | 20 | | | |
| 242 | SWT 848 | 100 | y | 273 | 120 | 56 | | | | 1.8 | 1.1 | 41 | 0.1 | 0.1 | 54 | | | |
| 302 | NONE | 0 | n | 189 | 149 | 21 | 19 | 14 | 28 | 1.3 | 1.2 | 8 | 0.6 | 0.6 | 10 | 3.5 | 2.4 | 33 |
| 302 | IRON | 10 | n | 202 | 151 | 25 | 6 | 13 | -111 | 1.5 | 1.3 | 14 | 0.6 | 0.5 | 15 | 13.3 | 10.5 | 21 |
| 302 | IRON | 25 | n | 257 | 183 | 29 | 9 | 7 | 19 | 1.8 | 1.5 | 16 | 0.9 | 0.8 | 14 | 28.5 | 25.5 | 11 |
| 302 | SWT 848 | 100 | y | 304 | 121 | 60 | | | | 2.0 | 1.1 | 44 | 0.8 | 0.1 | 87 | | | |
| 302 | SWT 848 | 100 | n | 202 | 127 | 37 | | | | 1.5 | 1.1 | 26 | 0.2 | 0.1 | 59 | | | |

Table A2. Conductivity data for conservative tracer experiments.

| Time Seconds | 145 um/sec No Baffle | 145 um/sec Baffle | 205 um/sec Baffle | 205 um/sec Baffle | 205 um/sec No Baffle | 302 um/sec Baffle | 302 um/sec Baffle | 302 um/sec No Baffle | 302 um/sec No Baffle |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 300 | 390 | 270 | 275 | 270 | 300 | 260 | 260 | 260 |
| 5 | 300 | 390 | 270 | 275 | 270 | 300 | 260 | 260 | 260 |
| 10 | 300 | 390 | 270 | 275 | 310 | 300 | 260 | 260 | 260 |
| 20 | 300 | 390 | 270 | 275 | | 300 | 260 | 700 | 1500 |
| 25 | 300 | 390 | 270 | 275 | 1700 | 300 | 260 | 1400 | 1350 |
| 30 | 300 | 390 | 270 | 275 | 1200 | 300 | 260 | 1200 | 1150 |
| 35 | 300 | 390 | 270 | 275 | 1100 | 300 | 260 | 1175 | 1000 |
| 40 | 300 | 390 | 270 | 275 | 900 | 300 | 260 | 1000 | 900 |
| 45 | 300 | 390 | 270 | 275 | 900 | 300 | 260 | 900 | 700 |
| 50 | 300 | 390 | 270 | 275 | 800 | 300 | 260 | 800 | 700 |
| 55 | 325 | 390 | 270 | 275 | 800 | 300 | 260 | 700 | 700 |
| 60 | 325 | 400 | 400 | 275 | 800 | 300 | 260 | 625 | 675 |
| 65 | 325 | 400 | 400 | 300 | | 300 | 260 | 700 | 630 |
| 70 | 325 | 400 | 400 | 300 | 700 | 325 | 260 | 600 | 620 |
| 75 | 325 | 400 | 460 | 300 | | 300 | 260 | 600 | 650 |
| 80 | 325 | 400 | 800 | 300 | 600 | 300 | 300 | 600 | 625 |
| 85 | 300 | 400 | 1000 | 600 | 700 | 400 | 300 | 650 | 700 |
| 90 | 325 | 400 | 800 | 700 | 650 | 400 | 400 | 650 | 700 |
| 95 | 350 | 400 | 800 | 800 | 700 | 400 | 850 | 650 | 700 |
| 100 | 350 | 400 | 850 | 900 | 700 | 650 | 650 | 700 | 690 |
| 105 | 350 | 400 | | 900 | 750 | 800 | 850 | 700 | 690 |
| 110 | 350 | 400 | 600 | 1100 | | 750 | 1100 | 700 | 680 |
| 115 | 400 | 400 | | 1050 | | 800 | | 700 | 680 |
| 120 | 450 | 400 | 650 | 1100 | | 1000 | 950 | 700 | 650 |
| 125 | 490 | 400 | | | | 950 | 950 | 650 | |
| 130 | 390 | 400 | 750 | 1100 | | 1100 | 1150 | 650 | 630 |
| 135 | 400 | 400 | | 900 | 700 | 1200 | 1100 | 600 | |
| 140 | 700 | 400 | 700 | 850 | | 1150 | 950 | 600 | 620 |
| 145 | 800 | 400 | | 800 | | 975 | 900 | 600 | |
| 150 | 850 | 400 | 650 | | | 1050 | 900 | 600 | 620 |
| 155 | 900 | 400 | | | | 1000 | 900 | 600 | |
| 160 | 850 | 400 | 700 | | | 1000 | 900 | 600 | 610 |
| 165 | 800 | 400 | | | | 1000 | 1000 | 600 | |
| 170 | 800 | 400 | 700 | | | 950 | 950 | 600 | 600 |
| 175 | 800 | 400 | | | 700 | 1000 | 800 | 600 | |
| 180 | 800 | 450 | 600 | 800 | | 850 | 825 | 600 | 590 |
| 185 | 800 | | | | | 800 | 875 | | |
| 190 | 800 | 500 | 600 | 800 | 650 | 850 | 825 | | |
| 195 | 800 | 490 | | | | 700 | 750 | | |
| 200 | 800 | 490 | 600 | 700 | | 600 | 700 | | |
| 205 | 800 | 475 | | | | 600 | 735 | | |
| 210 | 800 | 475 | 700 | 650 | | 650 | 725 | 575 | 580 |
| 215 | 800 | 475 | | | | 650 | | | |
| 220 | 750 | 490 | | | | 650 | 600 | | |
| 225 | 750 | 500 | | | | 700 | | | |
| 230 | 750 | 500 | 700 | | | 750 | | | |
| 235 | 750 | 525 | | | 610 | 700 | | | |
| 240 | 750 | 525 | 700 | 600 | 610 | 625 | 600 | 550 | 550 |
| 250 | 800 | 500 | 600 | | | 600 | | | |
| 260 | 800 | 500 | 600 | | | 650 | | | |
| 270 | 800 | 490 | 600 | 600 | 600 | 700 | 550 | 510 | 510 |
| 280 | 800 | 450 | 600 | | | 600 | | | |

25

Table A3.  Hydrometer data for sediment particle size determination

| Elapsed time (min) | Reading (Sample #1) | Reading (Sample #2) | Rc (Sample #1) | Rc (Sample #2) | L (Sample #1) (cm) | L (Sample #2) (cm) | Dia. (Sample #1) (mm) | % Finer (Sample #1) | Dia. (Sample #2) (mm) | % Finer (Sample #2) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 37.0 | 39.0 | 32.5 | 35.0 | 11.0 | 10.5 | 0.0431 | 65 | 0.0421 | 70 |
| 2 | 30.0 | 32.0 | 25.5 | 28.0 | 12.1 | 11.7 | 0.0320 | 51 | 0.0314 | 56 |
| 4 | 24.0 | 25.5 | 19.5 | 21.5 | 13.1 | 12.8 | 0.0235 | 39 | 0.0233 | 43 |
| 8 | 19.0 | 20.0 | 14.5 | 16.0 | 13.9 | 13.7 | 0.0171 | 29 | 0.0170 | 32 |
| 15 | 16.0 | 16.5 | 11.5 | 12.5 | 14.4 | 14.3 | 0.0127 | 23 | 0.0127 | 25 |
| 30 | 13.0 | 13.5 | 8.5 | 9.5 | 14.9 | 14.8 | 0.0092 | 17 | 0.0091 | 19 |
| 60 | 10.5 | 11.0 | 6.0 | 7.0 | 15.3 | 15.2 | 0.0066 | 12 | 0.0065 | 14 |
| 120 | 9.5 | 9.5 | 5.0 | 5.5 | 15.5 | 15.4 | 0.0047 | 10 | 0.0047 | 11 |
| 240 | 8.0 | 9.0 | 3.5 | 5.0 | 15.7 | 15.5 | 0.0033 | 7 | 0.0033 | 10 |
| 1080 | 8.0 | 8.0 | 3.5 | 4.0 | 15.7 | 15.6 | 0.0016 | 7 | 0.0016 | 8 |

Table A4.  Lead and zinc adsorption data as a function of sediment particle size.

| Diameter (um) | Solids (g/l) | Pb TM (mg/l) | Zn TM (mg/l) | Zn LM (mg/l) | Zn Sorbed (mg/l) | Pb (mg/g) | Zn (mg/g) |
|---|---|---|---|---|---|---|---|
| 3.44 | 0.245 | 4.6 | 4.5 | 2.7 | 1.8 | 18.8 | 7.3 |
| 3.45 | 0.275 | 4.7 | 4.5 | 2.7 | 1.9 | 16.9 | 6.8 |
| 4.72 | 0.335 | 5.7 | 5.0 | 2.7 | 2.4 | 17.0 | 7.0 |
| 6.74 | 1.225 | 10.6 | 7.4 | 2.7 | 4.7 | 8.6 | 3.8 |
| 7.31 | 1.38 | 11.0 | 7.6 | 2.6 | 4.9 | 8.0 | 3.6 |
| 8.48 | 0.925 | 10.0 | 7.0 | 2.8 | 4.2 | 10.8 | 4.5 |
| 8.77 | 0.675 | 8.3 | 6.1 | 2.7 | 3.5 | 12.2 | 5.1 |
| 8.85 | 0.655 | 8.8 | 6.5 | 2.8 | 3.7 | 13.4 | 5.6 |
| 8.87 | 0.585 | 8.1 | 6.2 | 2.8 | 3.4 | 13.9 | 5.7 |
| 9.17 | 0.705 | 8.9 | 6.5 | 2.8 | 3.7 | 12.6 | 5.2 |
| 10.92 | 0.97 | 10.0 | 7.1 | 2.7 | 4.4 | 10.3 | 4.5 |
| 17.61 | 13.76 | 44.7 | 24.9 | 2.7 | 22.2 | 3.2 | 1.6 |